National Aeronautics and Space Administration

Starling Mission: ROMEO Experiment for Autonomous Swarm Control

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Outline

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  - Motivation
  - Swarm Overview
- ROMEO Overview
  - Objective
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- Future Work

Starling Summary

- Multi-CubeSat mission to demonstrate swarm technologies
  - 4 – 6U spacecraft
  - 550km Sun-Synchronous orbit
  - 26-week mission set to launch in mid-2022
  - Four onboard experiments

Starling Partners

Partners	Role
NASA Ames Research Center	Project Management Systems Engineering Payload Avionics & Software Propulsion System Spacecraft I&T Mission & Experiment Operations
Blue Canyon Technologies	Spacecraft Bus Spacecraft Operations
NASA Launch Services Program Launch Provider: Firefly Black Launch Integrator: Nanoracks	Launch
Stanford University	Relative Navigation Experiment
Emergent Space Technologies Inc.	Cluster Management Software
CesiumAstro Inc.	Crosslink Radios
L3 Harris	Flight Dynamics System Development

Starling Motivation

Starling is a tech demo to advance technologies in autonomous swarm control

- Swarms are becoming more popular
- Large swarms of spacecraft require more effort to maintain
- More effort to maintain means more people
- As swarms become more prevalent, technologies to control and maintain large swarms will need to be developed.

Onboard Experiments

Experiments	Partner	Approach
ROMEO - Onboard Cluster Flight Control	Emergent – Cluster Flight Application (CFA) Software	Implement CFA in Payload software and demonstrate automated cluster station-keeping
MANET - Crosslink/ Networking	CesiumAstro – CommPack S-band Crosslink Radio	Implement BATMAN networking protocol and demonstrate onboard network management
DSA - Distributed Spacecraft Autonomy	DSA Project out of NASA Game Changing Development (GCD) Program	Detect Total Electron Count (TEC) using bus L1/L2 GPS receiver, and have swarm autonomously change observation tactics
StarFOX - Relative Navigation	Stanford – Dr. Simone D’Amico for Relative Navigation algorithms	Use bus star tracker to image fellow swarm S/C over multiple orbits and run payload software to determine relative position

Swarm vs. Constellation

Swarm

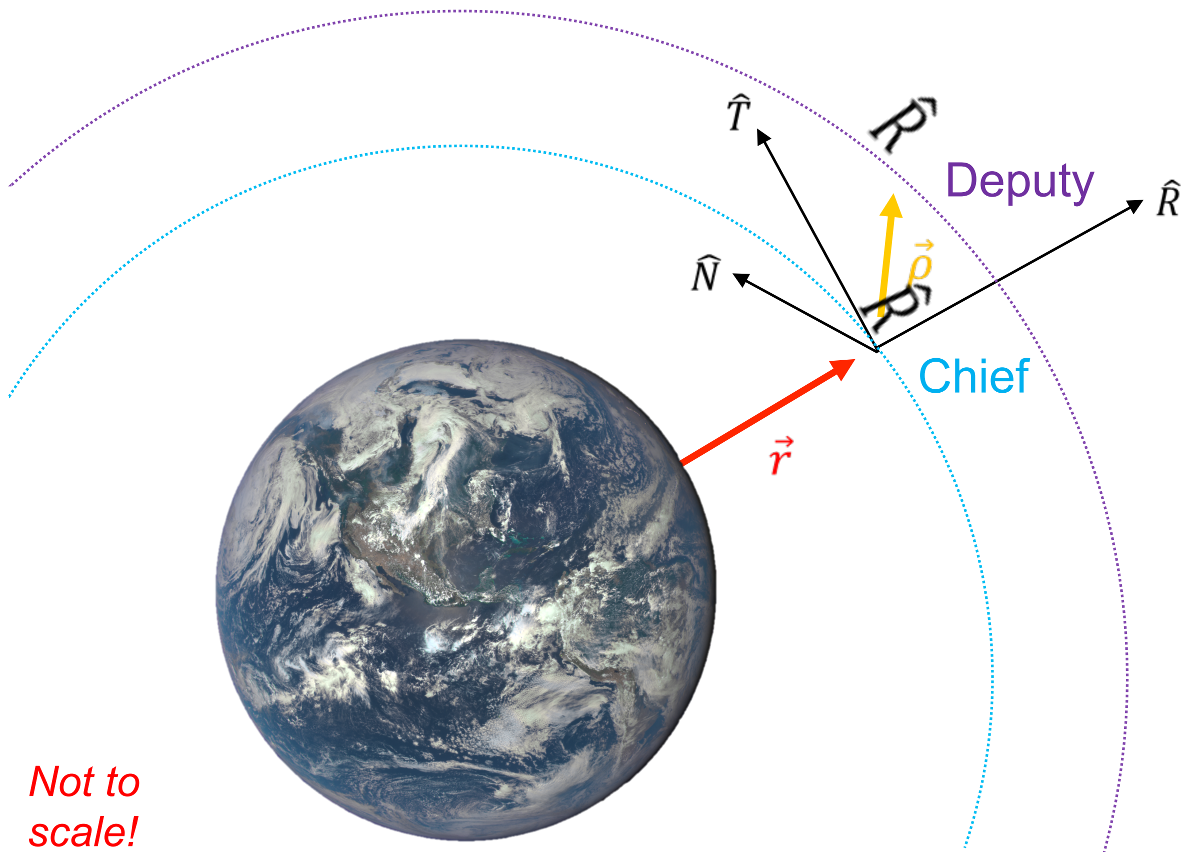
- 2+ distributed spacecraft
- Relative navigation and control
- Inter-satellite distance magnitude is fraction of orbital distance

Constellation

- 2+ distributed spacecraft
- Inter-satellite distance magnitude is same as orbital distance

Hill Frame

- Relative motion modeled in the Hill frame (sometimes referred to as RIC, LVLH)
  - Note: tangential direction is not the same as the in-track direction for non-circular orbits, relative motion analysis frequently assumes circular orbits (e~0)



Radial direction lies along position vector to chief

Tangential direction completes the right-handed triad

Normal direction lies along the chief orbit normal

Relative Orbital Elements

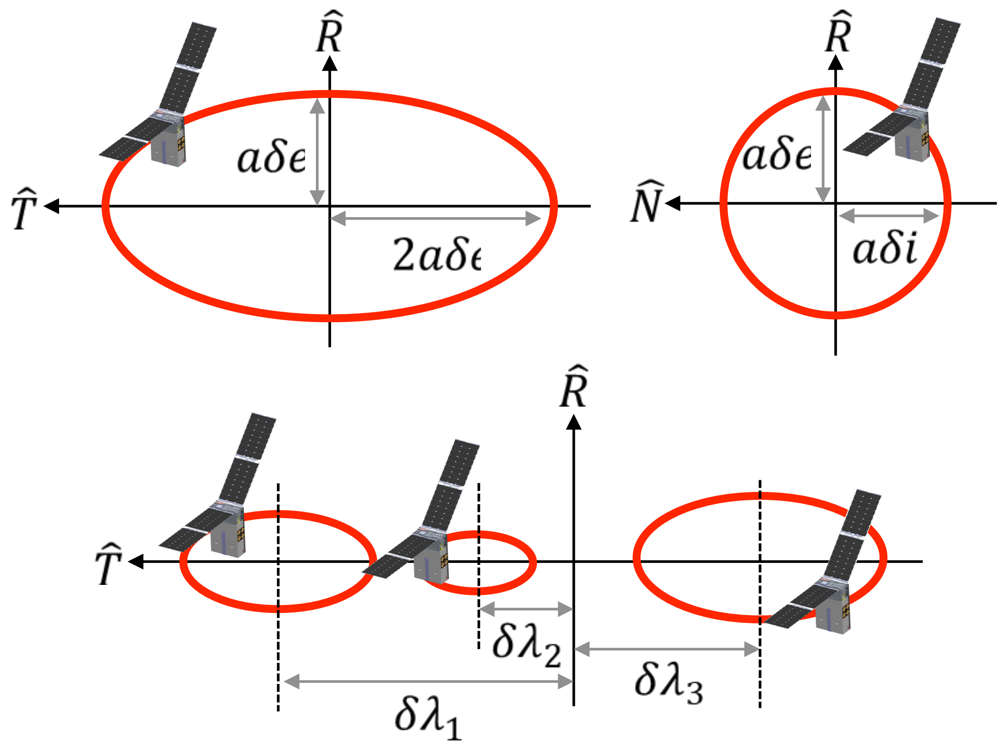
- Starling formation designed using **relative orbital elements (ROE)** as articulated by D'Amico and Montenbruck
- ROE derived from inclination and eccentricity vectors
  - ϕ is the relative eccentricity phase angle (function of Δe and $\Delta\omega$)
  - θ is the argument latitude where the chief and deputy orbital planes intersect

$$\{\delta a, \delta e_x, \delta e_y, \delta i_x, \delta i_y, \delta\lambda\}$$

- First five ROE describe cyclical RT and RN plane motion
- $\delta\lambda$ describes offset along the T axis

$$\overrightarrow{\delta e} = \begin{Bmatrix} \delta e_x \\ \delta e_y \end{Bmatrix} = \delta e \begin{Bmatrix} \cos\phi \\ \sin\phi \end{Bmatrix}$$

$$\overrightarrow{\delta i} = \begin{Bmatrix} \delta i_x \\ \delta i_y \end{Bmatrix} = \sin\delta i \begin{Bmatrix} \cos\theta \\ \sin\theta \end{Bmatrix}$$



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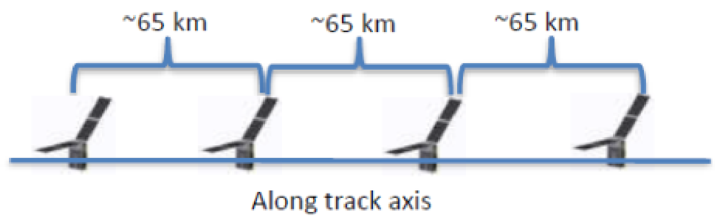
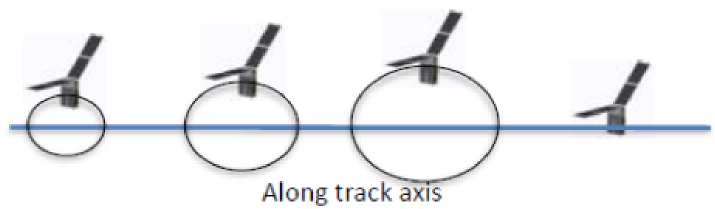
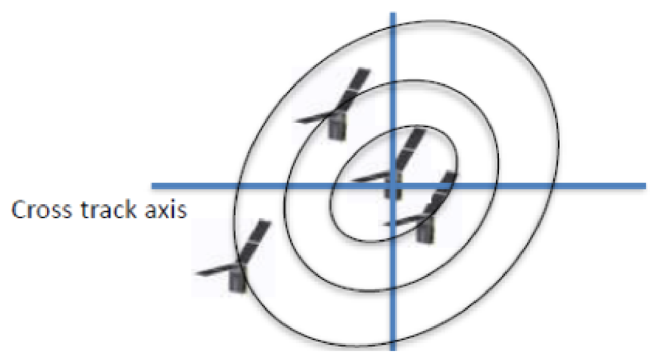
Swarm Design

- Three different configurations throughout the mission
  - 4 Weeks of In-train
  - 7 Weeks of passive safety ellipses (PSE) configuration 1
  - 5 Weeks of PSE-2
- Minimum inter-satellite distance of 63 km
- Maximum inter-satellite distance of 200 km







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ROMEO Overview

ROMEO (**R**econfiguration and **O**rbit **M**aintenance **E**xperiments **O**nboard) is an experimental software payload to **demonstrate autonomous swarm maneuver planning and execution.**

Objectives:

- Perform autonomous relative orbit maintenance with respect to a reference ephemeris
- Perform autonomous swarm maintenance with respect to a specified reference spacecraft
- Perform autonomous swarm reconfiguration to a new, specified formation

Autonomous Mission Operations

- Process for maintaining a swarm is the same regardless of what is performing the maintenance
- Ground utilizes the Flight Dynamics System
- ROMEO utilizes onboard software (Cluster Flight Application)

Determine S/C orbits	Evaluate current vs. desired ROE	Create maneuver plans	Swarm S/C execute maneuvers
Filter GPS data to determine the absolute orbits of all spacecraft, compute relative position of spacecraft in swarm	Compute ROE relative to either a selected spacecraft or a "virtual" reference, compare to desired ROE	Given initial state, compute maneuver(s) for spacecraft to achieve desired final state, accounting for propulsion performance	Generate command for spacecraft to execute maneuver, uplink/transfer to S/C CDH, perform required burns

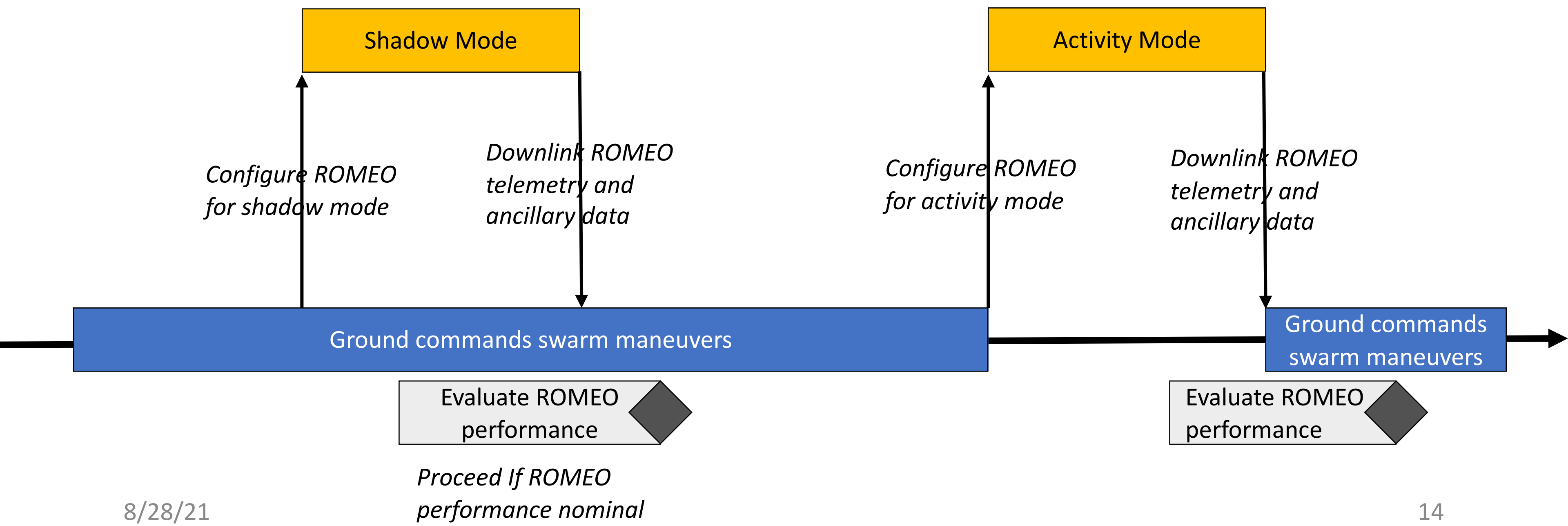
Cluster Flight Application

- Developed by Emergent Space technologies
- Modular autonomous control system that ROMEO utilizes
  - Calculates spacecraft position from onboard GPS measurements
  - Determines if maneuver is necessary
  - Computes optimal maneuvers through simulated annealing
  - Coordinates maneuver across all vehicles in the swarm

Experiment Approach

ROMEO includes multiple cycles to demonstrate increasing degrees of onboard autonomy.

- Shadow Mode
  - Demonstrate experiment configuration validity
- Activity Mode
  - Demonstrate experiment configuration performance

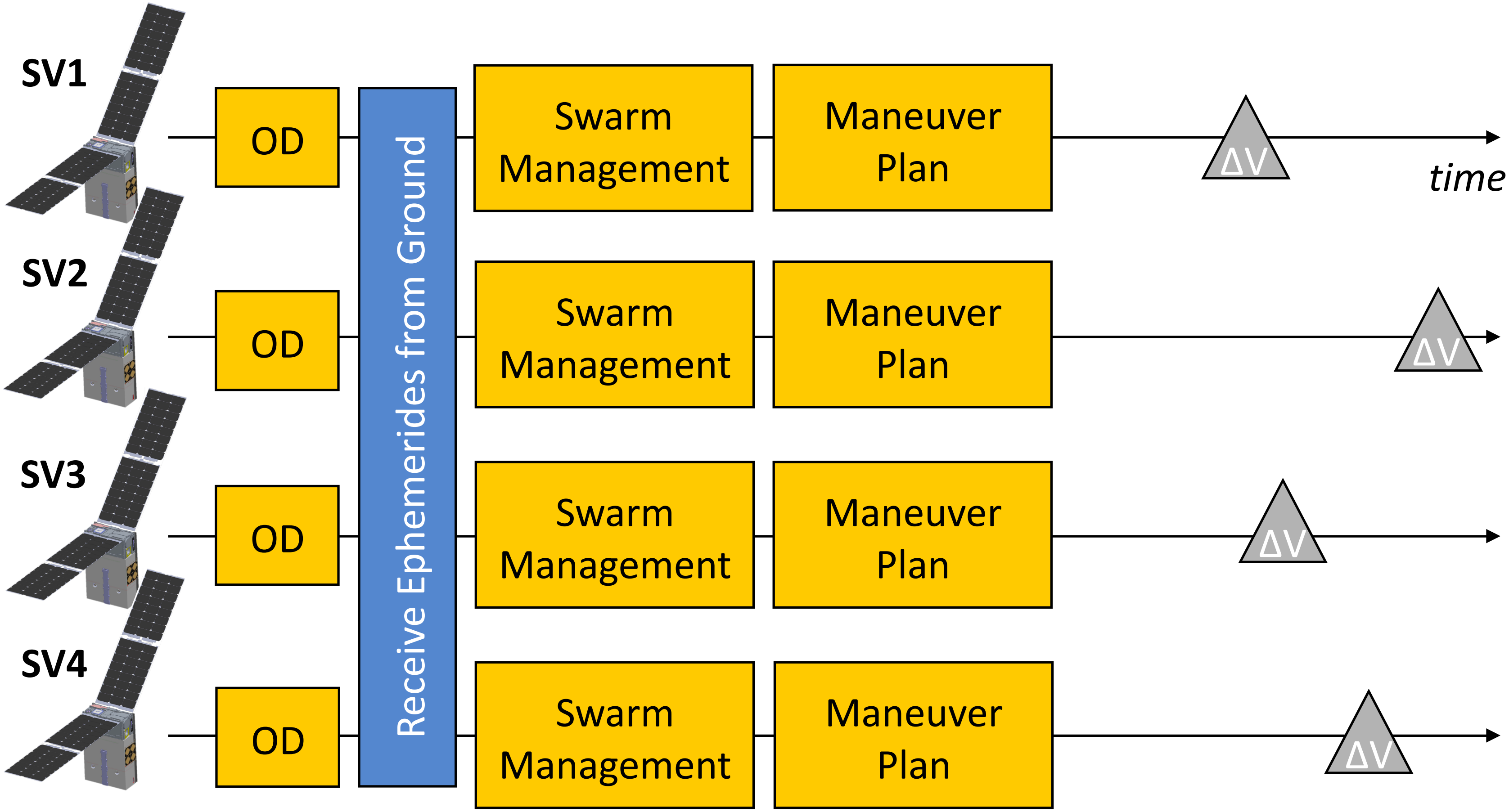


Experiment Phases

- Baseline plan for ROMEO includes 4 experiment configurations
  - May be executed multiple times and/or in different formation phases

Exp't	Formation	Mode	Crosslink	Passively Safe?
1	In-Train	Maintenance	No	No
2	PSE-1	Maintenance	No	Yes
3	PSE-1 or -2	Maintenance	Yes	Yes
4	PSE-2	Reconfiguration	Yes	Yes

Non-Crosslink Enabled Experiment



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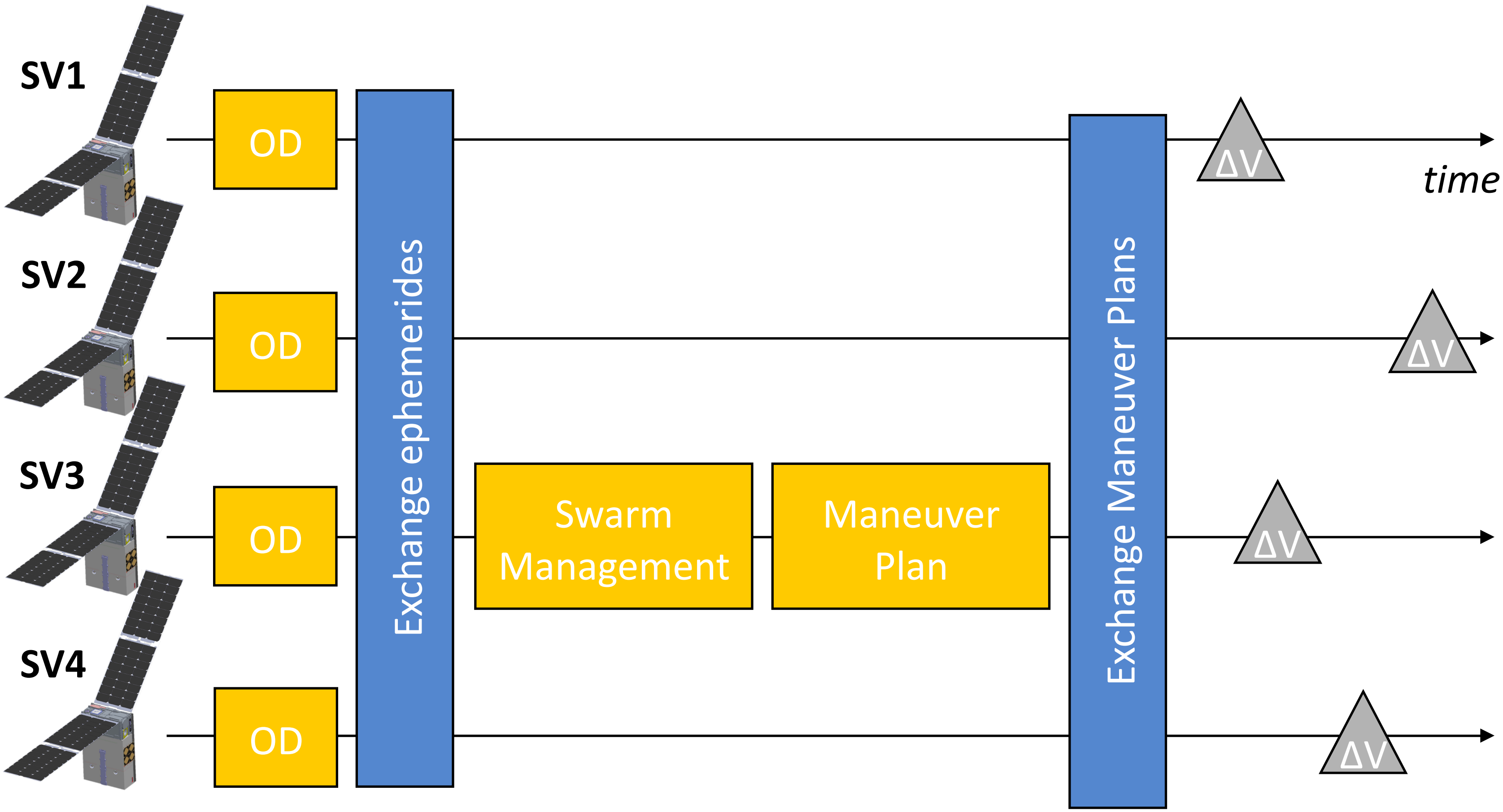
Crosslink Enabled Experiment



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Evaluation Criteria

- Quantitative comparison between ground commanded maneuvers and autonomous formation maintenance

Performance	Metric	Data Source
Swarm Maintenance Efficiency	ΔV [cm/s]	Commanded maneuvers
Swarm Maintenance Accuracy	σ_{ROE} [n.d.]	Definitive ephemerides
Swarm Maintenance Complexity	n_{mnvrs} [n.d.]	Commanded maneuvers

Experiment Challenges

- Crosslink is necessary for full demonstration of autonomous capability
  - During earlier stages of the mission, Crosslink radios are not available
  - CFA can operate each vehicle independently of each other but requires knowledge of other vehicle positions
- Two autonomously operated swarms pose significant risk to each other
  - No cross-swarm communication
  - Mitigated by screening Starling maneuvers on the ground
    - Large impact on experiment ConOps
    - Impacts CFA performance

Experiment ConOps

1. Ground uploads CFA configuration prior to experiment window
2. CFA Generates a maneuver plan
   - 1+ hours
3. Plan is screened by ground for potential collisions
   - 7+ hours
4. 24-hour notification period for maneuvers to be distributed to relevant parties
   - Allows for abort command to be sent
5. Maneuvers executed
6. Ground performs orbit determination and evaluates maneuver performance

Future Work and Goals

- System to have distinct swarms communicate with each other needs to be developed
- As technology gains maturity need for ground validation is reduced
- Use demonstrated technologies on larger swarms

Questions?